

EE C247B - ME C218 Introduction to MEMS Design Spring 2020


Prof. Clark T.-C. Nguyen

Dept. of Electrical Engineering & Computer Sciences
University of California at Berkeley
Berkeley, CA 94720

Lecture Module 5: Surface Micromachining

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Lecture Outline

- Reading: Senturia Chpt. 3, Jaeger Chpt. 11, Handout: "Surface Micromachining for Microelectromechanical Systems"
- Lecture Topics:
 - ↕ Polysilicon surface micromachining
 - ↕ Stiction
 - ↕ Residual stress
 - ↕ Topography issues
 - ↕ Nickel metal surface micromachining
 - ↕ 3D "pop-up" MEMS
 - ↕ Foundry MEMS: the "MUMPS" process
 - ↕ The Sandia SUMMIT process

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Polysilicon Surface-Micromachining

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- Uses IC fabrication instrumentation exclusively
- Variations: sacrificial layer thickness, fine- vs. large-grained polysilicon, *in situ* vs. $POCl_3$ -doping

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Polysilicon

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Why Polysilicon?

- Compatible with IC fabrication processes
 - ↖ Process parameters for gate polysilicon well known
 - ↖ Only slight alterations needed to control stress for MEMS applications
- Stronger than stainless steel: fracture strength of polySi ~ 2-3 GPa, steel ~ 0.2GPa-1GPa
- Young's Modulus ~ 140-190 GPa
- Extremely flexible: maximum strain before fracture ~ 0.5%
- Does not fatigue readily

- Several variations of polysilicon used for MEMS
 - ↖ LPCVD polysilicon deposited undoped, then doped via ion implantation, PSG source, POCl₃, or B-source doping
 - ↖ In situ-doped LPCVD polysilicon
 - ↖ Attempts made to use PECVD silicon, but quality not very good (yet) → etches too fast in HF, so release is difficult

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Polysilicon Surface-Micromachining Process Flow

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Layout and Masking Layers

- **At Left:** Layout for a folded-beam capacitive comb-driven micromechanical resonator
- **Masking Layers:**
 - 1st Polysilicon: POLY1(cf)
 - Anchor Opening: ANCHOR(df)
 - 2nd Polysilicon: POLY2(cf)
- Capacitive comb-drive for linear actuation
- Folded-beam support structure for stress relief

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Surface-Micromachining Process Flow

Cross-sections through A-A'

- Deposit isolation LTO (or PSG):
 - ⌘ Target = 2 μ m
 - ⌘ 1 hr. 40 min. LPCVD @450°C
- Densify the LTO (or PSG)
 - ⌘ Anneal @950°C for 30 min.
- Deposit nitride:
 - ⌘ Target = 100nm
 - ⌘ 22 min. LPCVD @800°C
- Deposit interconnect polySi:
 - ⌘ Target = 300nm
 - ⌘ In-situ Phosphorous-doped
 - ⌘ 1 hr. 30 min. LPCVD @650°C
- Lithography to define poly1 interconnects using the POLY1(cf) mask
- RIE polysilicon interconnects:
 - ⌘ CCl₄/He/O₂ @300W, 280mTorr
- Remove photoresist in PRS2000

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Surface-Micromachining Process Flow

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- Deposit sacrificial PSG:
 - ↳ Target = 2µm
 - ↳ 1 hr. 40 min. LPCVD @450°C
- Densify the PSG
 - ↳ Anneal @950°C for 30 min.
- Lithography to define anchors using the ANCHOR(df) mask
 - ↳ Align to the poly1 layer
- Etch anchors
 - ↳ RIE using CHF₃/CF₄/He @350W, 2.8Torr
 - ↳ Remove PR in PRS2000
 - ↳ Quick wet dip in 10:1 HF to remove native oxide
- Deposit structural polySi
 - ↳ Target = 2µm
 - ↳ In-situ Phosphorous-doped
 - ↳ 11 hrs. LPCVD @650°C

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Surface-Micromachining Process Flow

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- Deposit oxide hard mask
 - ↳ Target = 500nm
 - ↳ 25 min. LPCVD @450°C
- Stress Anneal
 - ↳ 1 hr. @ 1050°C
 - ↳ Or RTA for 1 min. @ 1100°C in 50 sccm N₂
- Lithography to define poly2 structure (e.g., shuttle, springs, drive & sense electrodes) using the POLY2(cf) mask
 - ↳ Align to the anchor layer
 - ↳ Hard bake the PR longer to make it stronger
- Etch oxide mask first
 - ↳ RIE using CHF₃/CF₄/He @350W, 2.8Torr
- Etch structural polysilicon
 - ↳ RIE using CCl₄/He/O₂ @300W, 280mTorr
 - ↳ Use 1 min. etch/1 min. rest increments to prevent excessive temperature

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Surface-Micromachining Process Flow

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- Remove PR (more difficult)
 - ↳ Ash in O_2 plasma
 - ↳ Soak in PRS2000
- Release the structures
 - ↳ Wet etch in HF for a calculated time that insures complete undercutting
 - ↳ If 5:1 BHF, then ~ 30 min.
 - ↳ If 48.8 wt. % HF, ~ 1 min.
- Keep structures submerged in DI water after the etch
- Transfer structures to methanol
- Supercritical CO_2 dry release

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Polysilicon Surface-Micromachined Examples

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- **Below:** All surface-micromachined in polysilicon using variants of the described process flow

Folded-Beam Comb-Driven Resonator

Free-Free Beam Resonator

Three-Resonator Micromechanical Filter

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Structural/Sacrificial Material Combinations

Structural Material	Sacrificial Material	Etchant
Poly-Si	SiO ₂ , PSG, LTO	HF, BHF
Al	Photoresist	O ₂ plasma
SiO ₂	Poly-Si	XeF ₂
Al	Si	TMAH, XeF ₂
Poly-SiGe	Poly-Ge	H ₂ O ₂ , hot H ₂ O

- Must consider other layers, too, as release etchants generally have a finite E.R. on any material
- Ex: concentrated HF (48.8 wt. %)
 - ↳ Polysilicon E.R. ~ 0
 - ↳ Silicon nitride E.R. ~ 1-14 nm/min
 - ↳ Wet thermal SiO₂ ~ 1.8-2.3 μm/min
 - ↳ Annealed PSG ~ 3.6 μm/min
 - ↳ Aluminum (Si rich) ~ 4 nm/min (much faster in other Al)

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Wet Etch Rates (f/ K. Williams)

ETCHANT EQUIPMENT CONDITIONS	TARGET MATERIAL	MATERIAL																
		SC Si <100>	Poly Si*	Poly Si**	Wet Ox.	Dry Ox.	LTO undop.	PSG undop.	PSG undop.	SiCN nitrid	Low-σ Nitrid	AV 2% Si	Sput Tung	Sput Ti	Sput Ti/W	OCO 820R	Olis HSPR	
Concentrated HF (49%) Wet Slick Room Temperature	Silicon oxides	-	0	-	23k 18k 23k	F	>14k	F	36k 140	52 30 52	42 0 42	<50	F	-	F	0	P	0
10:1 HF Wet Slick Room Temperature	Silicon oxides	-	7	0	230 230	230	340	15k 4700	11	3	2500 2500 12k	0	11k	<70	0	0	0	
25:1 HF Wet Slick Room Temperature	Silicon oxides	-	0	0	97 95	95	150	W 1500	6	1	W	0	-	-	-	0	0	
5:1 BHF Wet Slick Room Temperature	Silicon oxides	-	9	2	1000 900 1080	1000	1200	6800 4400 4400	9 3 4	4	1400 0.25 20	<20	F	1000	0	0	0	
Phosphoric Acid (85%) Heated Bath with Reflux 100°C	Silicon nitrides	-	7	-	0.7 0.8	0.8	<1	37 24 9 24 42 42	28 19 9 28 19 24 42 42	19	9800	-	-	-	550	390	0	
Silicon Etchant (126 HNO ₃ : 66 H ₂ O : 5 NH ₄ F) Wet Slick Room Temperature	Silicon	1500	3100	1000	87	W	110	4000 1700	2	3	4000	130	3000	-	-	0	0	
KOH (1 KOH : 2 H ₂ O by weight) Heated Stirred Bath 80°C	<100> Silicon	14k	>10k	F	77 41 77	-	94	W 380	0	0	F	0	-	-	F	F	0	
Aluminum Etchant Type A (16 H ₃ PO ₄ : 1 HNO ₃ : 1 HAc : 2 H ₂ O) Heated Bath 50°C	Aluminum	-	<10	<9	0	0	0	-	<10	0	2	6600 2600 6600	-	0	-	0	0	
Titanium Etchant (20 H ₂ O : 1 H ₂ O ₂ : 1 HF) Wet Slick Room Temperature	Titanium	-	12	-	120	W	W	W 2100	8	4	W	0	8800	-	-	0	0	
H ₂ O ₂ (30%) Wet Slick Room Temperature	Tungsten	-	0	0	0	0	0	0	0	0	0	<20	190 190 1000	0 60 150	60 60	<2	0	
Pinacid (-50 H ₂ SO ₄ : 1 H ₂ O ₂) Heated Bath 120°C	Cleaning off metals and organics	-	0	0	0	0	0	-	0	0	0	1800	-	2400	-	F	F	
Acetone Wet Slick Room Temperature	Photoresist	-	0	0	0	0	0	-	0	0	0	0	-	0	-	>4k	>30k	

Notations: -not not performed; W=not performed, but known to work (> 100 Å/min); F=not performed, but known to be flat (> 10 kÅ/min); P=some of film pitted during etch or when rinsed; A=film was visibly attacked and roughened.
 Each area was etched at a 4-inch width for the transparent films and half of the width for single-crystal silicon and the metals.
 Each rate will vary with temperature and prior use of solution, area of exposure of film, other materials present (e.g., photoresist, film impurities and microstructures, etc.). Some variation should be expected.

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Film Etch Chemistries

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- For some popular films:

Material	Wet etchant	Etch rate [nm/min]	Dry etchant	Etch rate [nm/min]
Polysilicon	HNO ₃ :H ₂ O: NH ₄ F	120-600	SF ₆ + He	170-920
Silicon nitride	H ₃ PO ₄	5	SF ₆	150-250
Silicon dioxide	HF	20-2000	CHF ₃ + O ₂	50-150
Aluminum	H ₃ PO ₄ :HNO ₃ : CH ₃ COOH	660	Cl ₂ + SiCl ₄	100-150
Photoresist	Acetone	>4000	O ₂	35-3500
Gold	KI	40	n/a	n/a

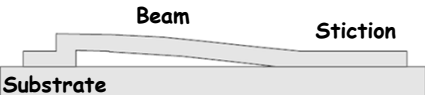
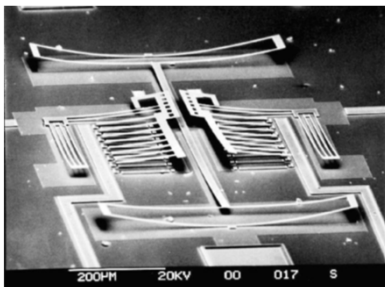

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Issues in Surface Micromachining

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- Stiction:** sticking of released devices to the substrate or to other on-chip structures
 - Difficult to tell if a structure is stuck to substrate by just looking through a microscope
- Residual Stress in Thin Films**
 - Causes bending or warping of microstructures
 - Limits the sizes (and sometimes geometries) of structures
- Topography**
 - Stringers can limit the number of structural levels

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Microstructure Stiction

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Microstructure Stiction

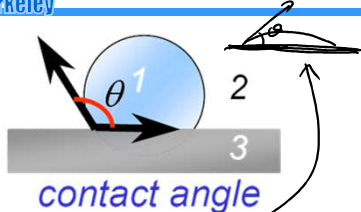
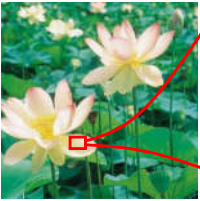

- **Stiction:** the unintended sticking of MEMS surfaces
- **Release stiction:**
 - ↳ Occurs during drying after a wet release etch
 - ↳ Capillary forces of droplets pull surfaces into contact
 - ↳ Very strong sticking forces, e.g., like two microscope slides w/ a droplet between
- **In-use stiction:** when device surfaces adhere during use due to:
 - ↳ Capillary condensation
 - ↳ Electrostatic forces
 - ↳ Hydrogen bonding
 - ↳ Van der Waals forces

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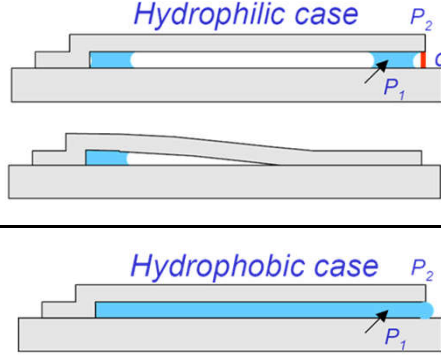
Hydrophilic Versus Hydrophobic

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Lotus Surface
[Univ. Mainz]

- **Hydrophilic:**
 - ↪ A surface that invites wetting by water
 - ↪ Get stiction
 - ↪ Occurs when the contact angle $\theta_{\text{water}} < 90^\circ$
- **Hydrophobic:**
 - ↪ A surface that repels wetting by water
 - ↪ Avoids stiction
 - ↪ Occurs when the contact angle $\theta_{\text{water}} > 90^\circ$

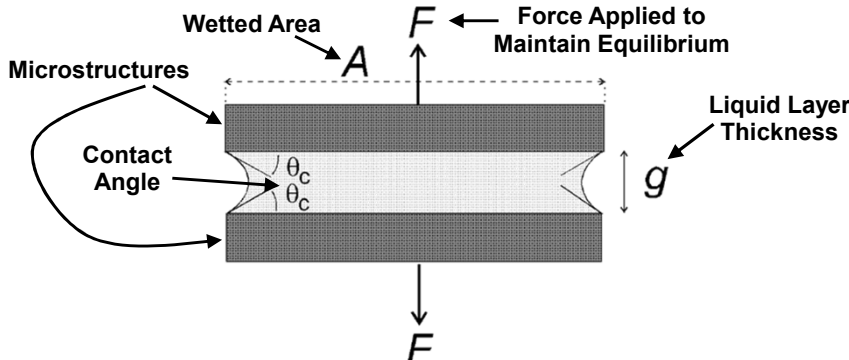


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Microstructure Stiction

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- Thin liquid layer between two solid plates \Rightarrow adhesive
- If the contact angle between liquid and solid $\theta_c < 90^\circ$:
 - ↪ Pressure inside the liquid is lower than outside
 - ↪ Net attractive force between the plates
- The pressure difference (i.e., force) is given by the Laplace equation

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Microstructure Stiction Modeling

Laplace Equation: Surface Tension @ the Liq-Air Interface F

$$\Delta p_{la} = \frac{\gamma_{la}}{r}$$

Δp_{la} ← Pressure Difference @ the Liquid-Air Interface
 r ← Radius of Curvature of the Meniscus (-) if concave

$$[r = -\frac{(g/2)}{\cos\theta_c}] \Rightarrow F = -\Delta p_{la} A = \frac{2A\gamma_{la}\cos\theta_c}{g}$$

Force needed to keep the plates apart
 $\Rightarrow (+)$ force means a
 $(-)$ Laplace pressure

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Avoiding Stiction

- Reduce droplet area via mechanical design approaches

- Avoid liquid-vapor meniscus formation
 - ↪ Use solvents that sublime
 - ↪ Use vapor-phase sacrificial layer etch
- Modify surfaces to change the meniscus shape from concave (small contact angle) to convex (large contact angle)
 - ↪ Use teflon-like films
 - ↪ Use hydrophobic self-assembled monolayers (SAMs)

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Supercritical CO₂ Drying

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- A method for stictionless drying of released microstructures by immersing them in CO₂ at its supercritical point
- **Basic Strategy:** Eliminate surface tension-derived sticking by avoiding a liquid-vapor meniscus
- **Procedure:**
 - ↪ Etch oxide in solution of HF
 - ↪ Rinse thoroughly in DI water, but do not dry
 - ↪ Transfer the wafer from water to methanol
 - ↪ Displace methanol w/ liquid CO₂
 - ↪ Apply heat & pressure to take the CO₂ past its critical pt.
 - ↪ Vent to lower pressure and allow the supercritical CO₂ to revert to gas → liquid-to-gas Xsition in supercritical region means no capillary forces to cause stiction

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Hydrophilic Versus Hydrophobic

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contact angle

- **Hydrophilic:**
 - ↪ A surface that invites wetting by water
 - ↪ Get stiction
 - ↪ Occurs when the contact angle $\theta_{\text{water}} < 90^\circ$
- **Hydrophobic:**
 - ↪ A surface that repels wetting by water
 - ↪ Avoids stiction
 - ↪ Occurs when the contact angle $\theta_{\text{water}} > 90^\circ$

Lotus Surface [Univ. Mainz]

Hydrophilic case *Hydrophobic case*

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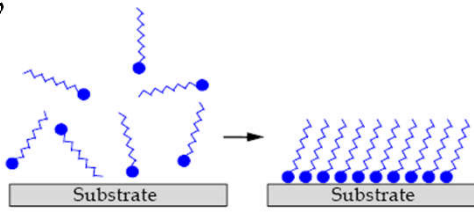
Tailoring Contact Angle Via SAM's

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- Can reduce stiction by tailoring surfaces so that they induce a water contact angle $> 90^\circ$

Self-Assembled Monolayers (SAM's):

- Monolayers of "stringy" molecules covalently bonded to the surface that then raise the contact angle
- Beneficial characteristics:
 - ↪ Conformal, ultrathin
 - ↪ Low surface energy
 - ↪ Covalent bonding makes them wear resistant
 - ↪ Thermally stable (to a point)



OTS
 $\text{CH}_3(\text{CH}_2)_{17}\text{SiCl}_3$

	θ_{water}
ODT SAM	$112 \pm 0.7^\circ$
SiO_2	$<10^\circ$

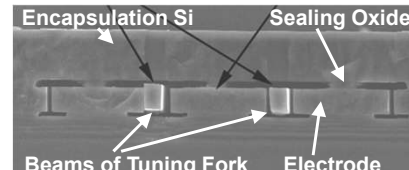
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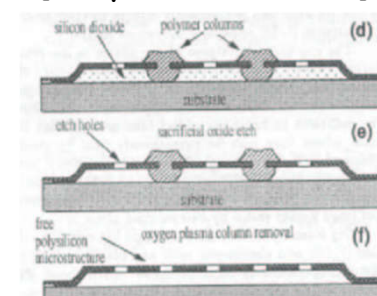
Dry Release

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- Another way to avoid stiction is to use a dry sacrificial layer etch
- For an oxide sacrificial layer
 - ↪ use HF vapor phase etching
 - ↪ **Additional advantage:** gas can more easily get into tiny gaps
 - ↪ **Issue:** not always completely dry → moisture can still condense → stiction → **soln:** add alcohol
- For a polymer sacrificial layer
 - ↪ Use an O_2 plasma etch (isotropic, so it can undercut well)
 - ↪ **Issues:**
 - Cannot be used when structural material requires high temperature for deposition
 - If all the polymer is not removed, polymer under the suspended structure can still promote stiction



Released via vapor phase HF
 [Kenny, et al., Stanford]



[Kobayashi]

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Residual Stress

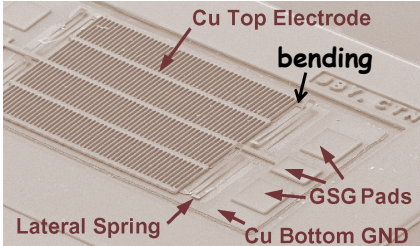
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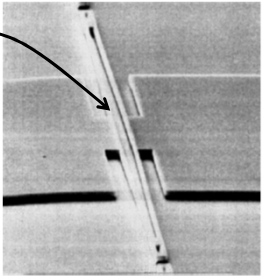
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Residual Stress in Thin Films

- After release, poorly designed microstructures might buckle, bend, or warp → often caused by residual film stress
- Origins of residual stress, σ
 - ↳ Growth processes
 - Non-equilibrium deposition
 - Grain morphology change
 - Gas entrapment
 - Doping
 - ↳ Thermal stresses
 - Thermal expansion mismatch of materials → introduce stress during cool-down after deposition
 - Annealing



Tunable Dielectric Capacitor [Yoon, et al., U. Michigan]



Buckled Double-Ended Tuning Fork

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Need to Control Film Stress

- Resonance frequency expression for a lateral resonator:

$$f_0 \approx \frac{1}{2\pi} \sqrt{\frac{4E_y t W^3}{ML^3} + \frac{24\sigma_r t W}{5ML}}$$

↑ ↑
 Basic Stress
 term term

Since $W \ll L$, the stress term will dominate if $\sigma_r \sim E_y$

E_y = Young's modulus
 σ_r = stress
 t = thickness
 W = beam width
 L = beam length
 M = mass

Folded-beam suspension Shuttle
 Anchor Folding truss

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Tensile Versus Compressive Stress

- Under tensile stress, a film wants to shrink w/r to its substrate
 - Caused, e.g., by differences in film vs. substrate thermal expansion coefficients
 - If suspended above a substrate and anchored to it at two points, the film will be "stretched" by the substrate
- Under compressive stress, a film wants to expand w/r to its substrate
 - If suspended above a substrate and anchored to it at two points, the film will buckle over the substrate

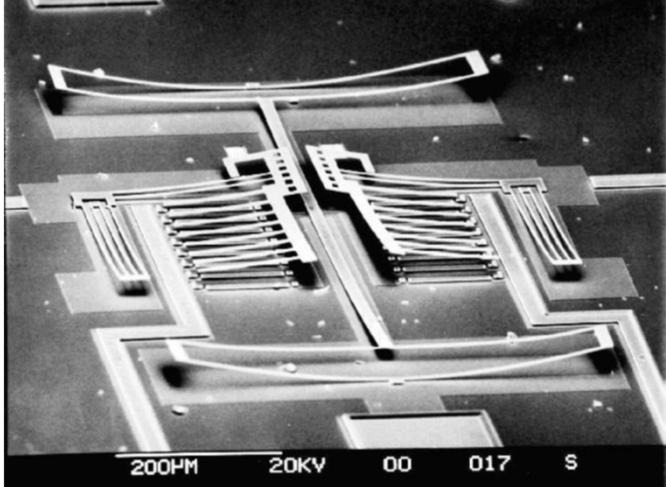
Si-substrate tensile film
 Si-substrate Si-substrate
 Si-substrate compressive film buckled
 Si-substrate

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 **Vertical Stress Gradients**

- Variation of residual stress in the direction of film growth
- Can warp released structures in z-direction



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 **Stress in Polysilicon Films**

- Stress depends on crystal structure, which in turn depends upon the deposition temperature
- Temperature $\leq 600^\circ\text{C}$
 - ↪ Films are initially amorphous, then crystallize
 - ↪ Get equiaxed crystals, largely isotropic
 - ↪ Crystals have higher density \rightarrow tensile stress
 - ↪ Small stress gradient
- Temperature $\geq 600^\circ\text{C}$
 - ↪ Columnar crystals grow during deposition
 - ↪ As crystals grow vertically and in-plane they push on neighbors \rightarrow compressive stress
 - ↪ Positive stress gradient

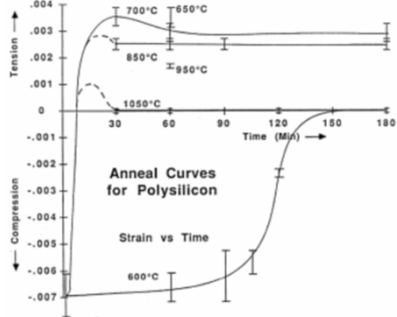
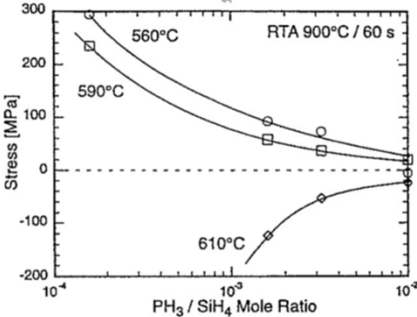
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Annealing Out Polysilicon Stress

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- Control polySi stress by annealing at high temperatures
 - Typical anneal temperatures: 900-1150°C
 - Grain boundaries move, relax
 - Can dope while annealing by sandwiching the polysilicon between similarly doped oxides (symmetric dopant drive-in), e.g. using 10-15 wt. % PSG

- Rapid thermal anneal (RTA) also effective (surprisingly)


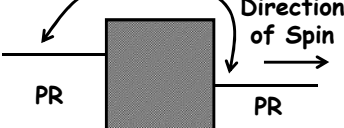
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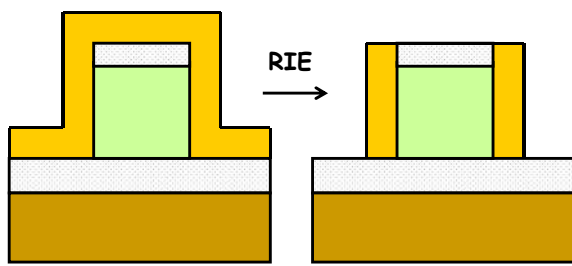
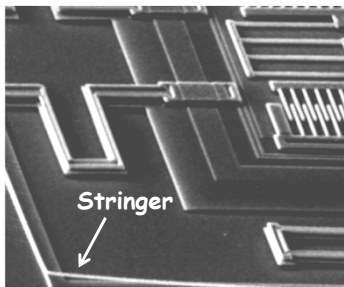
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Topography Issues

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- Degradation of lithographic resolution
 - PR step coverage, streaking
- Stringers
 - Problematic when using anisotropic etching, e.g., RIE

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Nickel Surface-Micromachining Process Flow

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Electroplating: Metal MEMS

- Use electroplating to obtain metal μ structures
- When thick: call it "LIGA"
- Pros: fast low temp deposition, very conductive
- Cons: drift, low mech. Q
 ↳ but may be solvable?

RF Switch

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Nickel Metal Surface-Micromachining

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- Deposit isolation LTO:
 - ↳ Target = 2µm
 - ↳ 1 hr. 40 min. LPCVD @450°C
- Densify the LTO
 - ↳ Anneal @950°C for 30 min.
- Define metal interconnect via lift-off
 - ↳ Spin photoresist and pattern lithographically to open areas where interconnect will stay
 - ↳ Evaporate a Ti/Au layer
 - Target = 30nm Ti
 - Target = 270nm Au
 - ↳ Remove photoresist in PRS2000 → Ti/Au atop the photoresist also removed

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Nickel Metal Surface-Micromachining

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- Evaporate Al to serve as a sacrificial layer
 - ↳ Target = 1µm
- Lithography to define anchor openings
- Wet etch the aluminum to form anchor vias
 - ↳ Use solution of $H_3PO_4/HNO_3/H_2O$
- Remove photoresist in PRS2000
- Electroplate nickel to fill the anchor vias
 - ↳ Use solution of nickel sulfamate @ 50°C
 - ↳ Time the electroplating to planarize the surface

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Nickel Metal Surface-Micromachining

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- Evaporate a thin film of nickel to serve as a seed layer for subsequent Ni electroplating
 - ↳ Target = 20nm
- Form a photoresist mold for subsequent electroplating
 - ↳ Spin 6 um-thick AZ 9260 photoresist
 - ↳ Lithographically pattern the photoresist to delineate areas where nickel structures are to be formed
- Electroplate nickel structural material through the PR mold
 - ↳ Use a solution of nickel sulfamate @ 50°C
 - ↳ Cathode-to-anode current density ~ 2.5 mA/cm²

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Nickel Metal Surface-Micromachining

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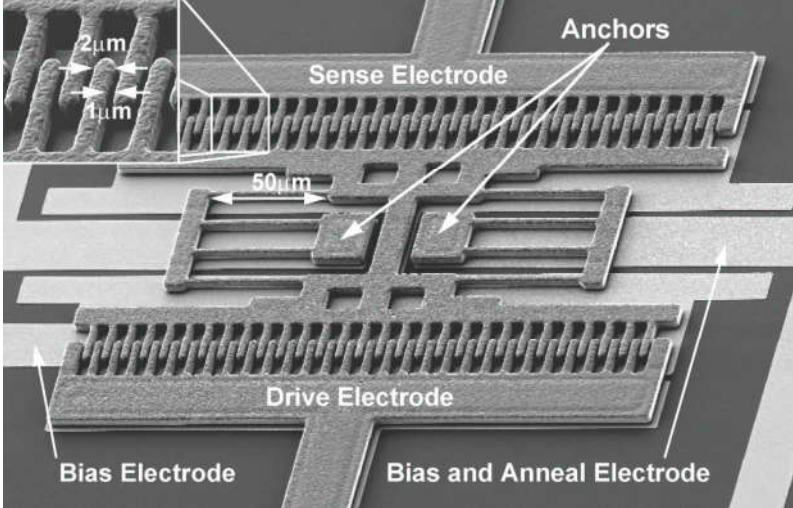
- Strip the PR in PRS2000
- Remove the Ni seed layer in Ni wet etchant
- Release the structures
 - ↳ Use a $K_4Fe(CN)_6/NaOH$ etchant that attacks Al while leaving Ni and Au intact
 - ↳ Etch selectivity > 100:1 for Al:Ni and Al:Au

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 **Nickel Surface-Micromachining Example**

- **Below:** Surface-micromachined in nickel using the described process flow



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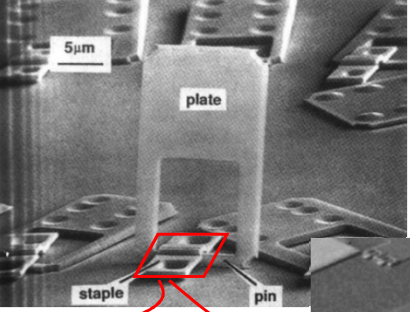
 **3D "Pop-up" MEMS**

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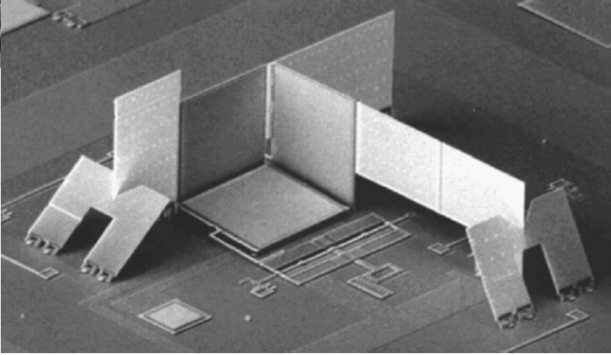
Pop-Up MEMS

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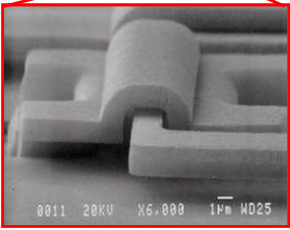


5µm
plate
staple
pin

First MEMS hinge
[K. Pister, et al., 1992]



Corner Cube Reflector
[v. Hsu, 1999]



0011 20KV X6,000 1µm WD25


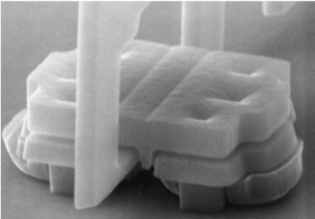
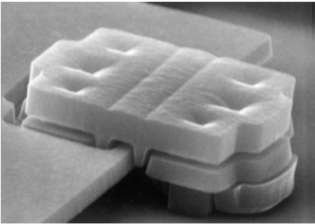
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Pop-Up MEMS

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- Pictured: hinged Campanile made in SUMMiT process, assembled using probes [Elliot Hui, et al.]



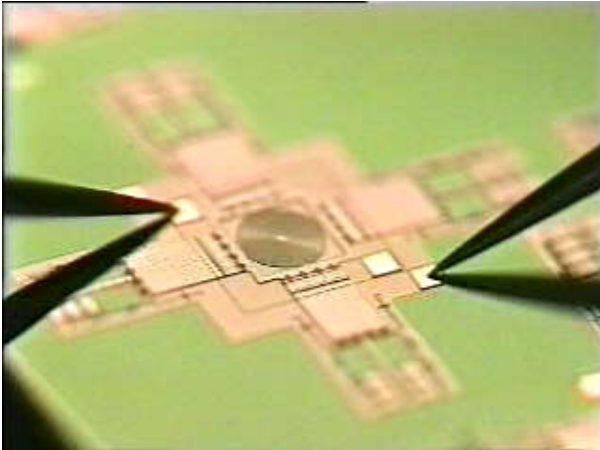
15KV X200 0009 100.0µm MSME

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3D Direct-Assembled Tunable L



[Ming Wu, UCLA]

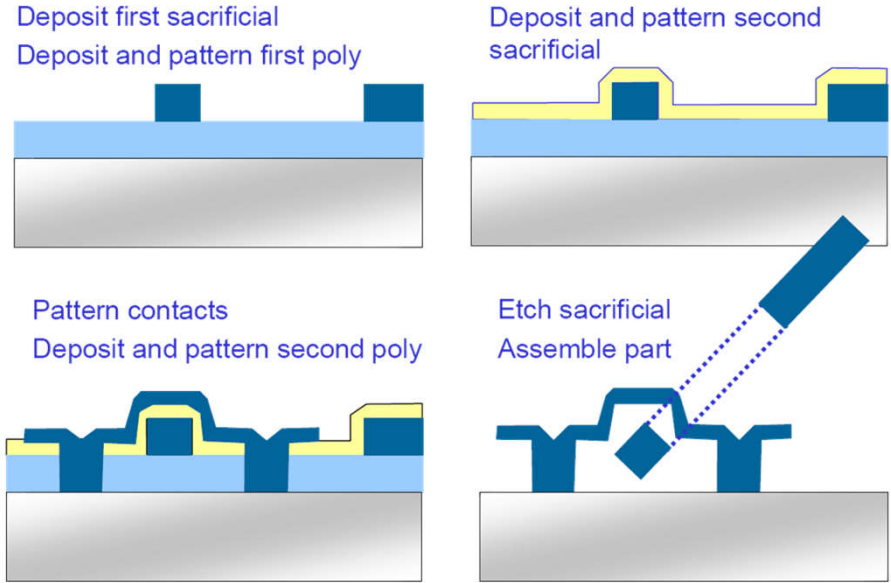
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This slide features a micrograph of a 3D direct-assembled tunable L device. The device is a complex, multi-layered structure with a central circular component and various rectangular and linear features. It is being held by two tweezers, indicating its small scale. The background is a blurred green surface.

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Hinge Process Flow



Deposit first sacrificial
Deposit and pattern first poly

Deposit and pattern second sacrificial

Pattern contacts
Deposit and pattern second poly

Etch sacrificial
Assemble part

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The diagram illustrates the four stages of the hinge process flow. Stage 1 shows a substrate with a first sacrificial layer (light blue) and a patterned first poly layer (dark blue). Stage 2 shows a second sacrificial layer (yellow) being deposited and patterned over the first poly. Stage 3 shows the formation of contacts (dark blue) and a second poly layer (yellow) being deposited and patterned. Stage 4 shows the sacrificial layer being etched away, and the final part being assembled.

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"Foundry" MEMS: The MUMPS Process

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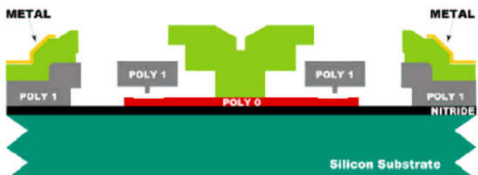
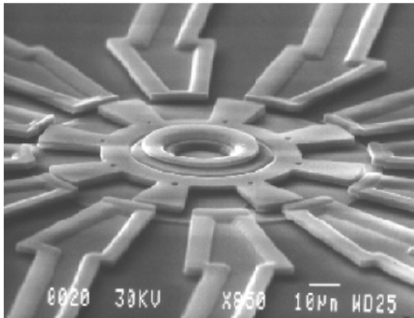
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MUMPS: MultiUser MEMS Process

- Originally created by the Microelectronics Center of North Carolina (MCNC) → now owned by MEMSCAP in France
- Three-level polysilicon surface micromachining process for prototyping and "foundry" services
- Designed to service as many users as possible; basically an attempt to provide a universal MEMS process
- 8 photomasks
- \$4,900 for 1 cm² dies

Micromotor fabricated via MUMPS



The diagram shows a cross-section of the MUMPS process layers: METAL, POLY 1, POLY 0, POLY 1, POLY 1, POLY 1, NITRIDE, and Silicon Substrate.

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MUMPS: MultiUser MEMS Process

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Micromotor Example

Material Layer	Thickness (μm)	Lithography Level Name
Nitride	0.6	--
Poly 0	0.5	POLY0 (HOLE0)
First Oxide	2.0	DIMPLE ANCHOR1
Poly 1	2.0	POLY1 (HOLE1)
Second Oxide	0.75	POLY1_POLY2_VIA ANCHOR2
Poly 2	1.5	POLY2 (HOLE2)
Metal	0.5	METAL (HOLEM)

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Masks in polyMUMPS

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Minimum set of masks that must be used in MUMPS

Mnemonic level name	Field type	Purpose
POLY0	light	pattern ground plane
ANCHOR1	dark	open holes for Poly 1 to Nitride or Poly 0 connection
DIMPLE	dark	create dimples/bushings for Poly 1
POLY1	light	pattern Poly 1
POLY1_POLY2_VIA	dark	open holes for Poly 1 to Poly 2 connection
ANCHOR2	dark	open holes for Poly 2 to Nitride or Poly 0 connection
POLY2	light	pattern Poly 2
METAL	light	pattern Metal
HOLE0	dark	provide holes for POLY0
HOLE1	dark	provide release holes for POLY1
HOLE2	dark	provide release holes for POLY2
HOLEM	dark	provide release holes in METAL

Extra masks for more flexibility & ease of release

- Field type:
 - ↪ **Light (or clear) field (cf):** in layout, boxes represent features that will stay through fabrication
 - ↪ **Dark field (df):** in layout, boxes represent holes to be cut out

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MUMPS Process Flow

The diagrams illustrate the following steps:

- Step 1:** Starting with a Silicon Substrate, a layer of NITRIDE is deposited. A Poly 0 mask is used for etching.
- Step 2:** A layer of 1st OXIDE is deposited over the nitride. The Poly 0 mask is used for etching to create a ground plane.
- Step 3:** A layer of 2nd OXIDE is deposited over the 1st oxide. The Poly 0 mask is used for etching to create dimples.
- Step 4:** A layer of 3rd OXIDE is deposited over the 2nd oxide. The Anchor 1 mask is used for etching to create anchor vias.

- Deposit PSG on the starting n-type (100) wafers
- Anneal to heavily dope the wafers
- Remove the PSG
- LPCVD 600 nm of low stress nitride
- LPCVD 500 nm of polysilicon
- Lithography using the POLY0(cf) mask and RIE etching to pattern the poly0 ground plane layer
- LPCVD 2 μm of PSG as the 1st sacrificial layer
- Lithography using the DIMPLE(df) mask (align to poly0)
- RIE 750 nm deep to form dimple vias
- Lithography using the ANCHOR1(df) mask (align to poly0)
- RIE anchor vias down to the nitride surface

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MUMPS Process Flow (cont.)

The diagrams illustrate the following steps:

- Step 5:** A layer of 4th OXIDE is deposited over the 3rd oxide. A PSG mask is used for etching to create a hard mask.
- Step 6:** A layer of POLY 1 is deposited over the 4th oxide. The POLY 1 mask is used for etching to define structures.
- Step 7:** A layer of 5th OXIDE is deposited over the POLY 1. The POLY 1 mask is used for etching to create P1_P2_Via structures.

- LPCVD 2 μm undoped polysilicon
- LPCVD 200 nm of PSG
- Anneal for 1 hr. @ 1050°C
 ↳ This both dopes the polysilicon and reduces its residual stress
- Lithography using the POLY1(cf) mask to define structures (align to anchor1)
- RIE the PSG to create a hard mask first, then ...
- RIE the polysilicon
- LPCVD 750 nm of PSG
- Lithography using the P1_P2_VIA(df) mask to define contacts to the poly1 layer (align to poly1)

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MUMPS Process Flow (cont.)

- Recoat with photoresist and do lithography using the ANCHOR2(df) mask to define openings where poly2 contacts nitride or poly0 (align to poly0)
- RIE the PSG at ANCHOR2 openings
- LPCVD 1.5 μm undoped polysilicon
- LPCVD 200 nm PSG as a hard mask and doping source
- Anneal for 1 hr @ 1050°C to dope the polysilicon and reduce residual stress
- Lithography using the POLY2(cf) mask (align to anchor2)
- RIE PSG hard mask
- RIE poly2 film
- Remove PR and hard mask

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MUMPS Process Flow (cont.)

- Lithography using the METAL (df) mask (align to poly2)
- Evaporate titanium (Ti) (as an adhesion layer for gold)
- Evaporate gold (Au)
- Liftoff to remove PR and define metal interconnects
- Coat wafers with protective PR
- Dice wafers
- Ship to customer
- Customer releases structures by dipping and agitating dies in a 48.8 wt. % HF solution or via vapor phase HF
- Anti-stiction dry, if needed

Final Structure: Micromotor

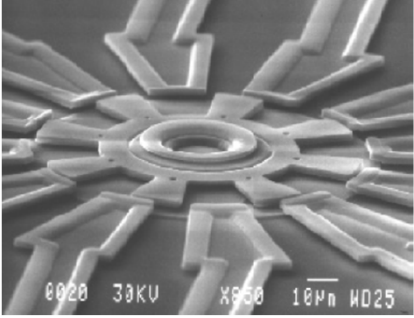

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MUMPS: MultiUser MEMS Process
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- Originally created by the Microelectronics Center of North Carolina (MCNC) → now owned by MEMSCAP in France
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- 8 photomasks
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Micromotor fabricated via MUMPS

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polyMUMPS Minimum Feature Constraints
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- Minimum feature size
 - ↳ Determined by MUMPS' photolithographic resolution and alignment precision
 - ↳ Violations result in missing (unanchored), under/oversized, or fused features
 - ↳ Use minimum feature only when absolutely necessary

	Nominal [μm]	Min Feature [μm]	Min Spacing [μm]
POLY0, POLY1, POLY2	3	2	2
POLY1_POLY2_VIA	3	2	2
ANCHOR1, ANCHOR2	3	3	2
DIMPLE	3	2	3
METAL	3	3	3
HOLE1, HOLE2	4	3	3
HOLEM	5	4	4

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MUMPS Design Rules (cont.)

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Rule	Rule Letter	Figure #	Min. Value (μm)
POLY0 space to ANCHOR1	A	2.5	4.0
POLY0 enclose ANCHOR1	B	2.5	4.0
POLY0 enclose POLY1	C	2.6	4.0
POLY0 enclose POLY2	D	2.7	5.0
POLY0 enclose ANCHOR2	E	2.8	5.0
POLY0 space to ANCHOR2	F	2.8	5.0

Cross Sections

Mask Levels

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MUMPS Design Rules (cont.)

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Rule	Min. Value (μm)
POLY1 enclose ANCHOR1	G 4.0
POLY1 enclose DIMPLE	N 4.0
POLY1 enclose POLY1_POLY2_VIA	H 4.0
POLY1 enclose POLY2	O 4.0
POLY1 space to ANCHOR2	K 3.0
*Lateral etch holes space in POLY1	R ≤ 30 (max. value)

Cross Sections

Mask Levels

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MUMPS Design Rules (cont.)

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Rule	Rule Letter	Figure #	Min. Value (μm)
POLY0 space to ANCHOR1	A	2.5	4.0
POLY0 enclose ANCHOR1	B	2.5	4.0
POLY0 enclose POLY1	C	2.6	4.0
POLY0 enclose POLY2	D	2.7	5.0
POLY0 enclose ANCHOR2	E	2.8	5.0
POLY0 space to ANCHOR2	F	2.8	5.0

Rule	Rule Letter	Figure #	Min. Value (μm)
POLY1 enclose ANCHOR1	G	2.6	4.0
POLY1 enclose DIMPLE	N	2.13	4.0
POLY1 enclose POLY1_POLY2_VIA	H	2.9, 2.11	4.0
POLY1 enclose POLY2	O	2.14	4.0
POLY1 space to ANCHOR2	K	2.11	3.0
*Lateral etch holes space in POLY1	R	2.15	≤30 (max. value)

Rule	Rule Letter	Figure #	Min. Value (μm)
POLY2 enclose ANCHOR2	J	2.7,2.10	5.0
POLY2 enclose POLY1_POLY2_VIA	L	2.9	4.0
POLY2 cut-in POLY1	P	2.14	5.0
POLY2 cut-out POLY1	Q	2.14	4.0
POLY2 enclose METAL	M	2.12	3.0
POLY2 space to POLY1	I	2.10	3.0
HOLE2 enclose HOLE1	T	2.16	2.0
HOLEM enclose HOLE2	U	2.16	2.0
*Lateral etch holes space in POLY2	S	2.15	≤30 (max. value)

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MUMPS Design Rules (cont.)

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Level 1	Level 2	Min. Feature	Min. Spacing	Enclose	Spacing	Cut-In	Cut-Out
POLY0	-	2	2				
	ANCHOR1			4/B/2.5	4/A/2.5		
	POLY1			4/C/2.6			
	ANCHOR2			5/E/2.8	5/F/2.8		
	POLY2			5/D/2.7			
POLY1	-	2	2 / 2.5 ²				
	POLY0						
	ANCHOR1			4/G/2.6			
	ANCHOR2				3/K/2.11		
	POLY2			4/O/2.14			
	DIMPLE			4/N/2.13			
	POLY1_POLY2_VIA			4/H/2.9			
POLY2	-	2	2 / 2.5 ²				
	POLY0						
	POLY1				3/I/2.10	5/P/2.14	4/Q/2.14
	VIA			4/L/2.9			
	ANCHOR2			5/J/2.7			
	METAL			3/M/2.12			
	HOLEM	HOLE2			2/U/2.16		
HOLE2	HOLE1			2/T/2.16			

TABLE 2.7. PolyMUMPs design rule reference sheet. Table shows minimum dimensions (μm), rule name, and figure number, respectively.

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The Sandia SUMMIT Process

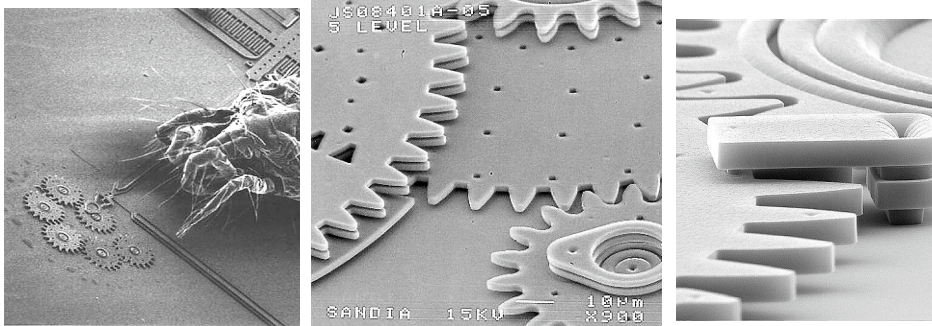
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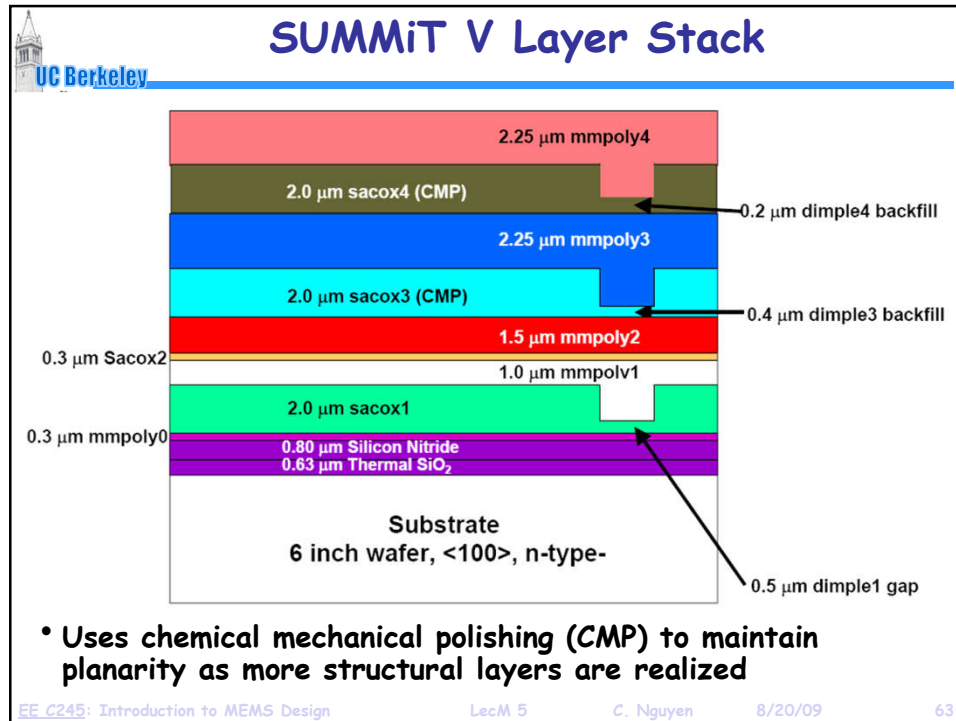
Sandia's SUMMIT V

- **SUMMIT V: "Sandia Ultra-planar Multi-level MEMS Technology 5" fabrication process**
 - ↪ Five-layer polysilicon surface micromachining process
 - ↪ One electrical interconnect layer & 4 mechanical layers
 - ↪ Uses chemical mechanical polishing (CMP) to maintain planarity as more structural layers are realized
 - ↪ 14 masks

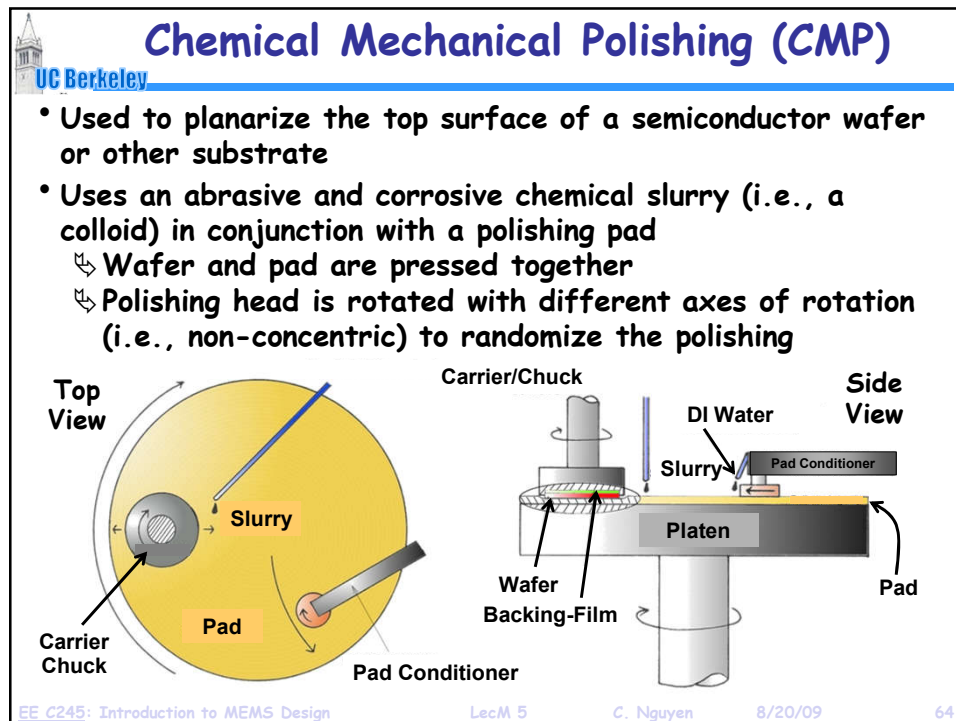


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CMP: Not the Same as Lapping

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Lapping

- Lapping is merely the removal of material to flatten a surface without selectivity
- Everything is removed at approximately the same rate

Lapping

Chemical Mechanical Polishing

- CMP is selective to certain films, and not selective to others

Stops at non-selective layer

CMP

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Actual SUMMiT Cross-Section

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- No CMP until after the first three polySi layers
- 1 μm mmpoly1 and 1.5 μm mmpoly2 can be combined to form a 2.5 μm polysilicon film
- Refer to the SUMMiT V manual (one of your handouts) for more detailed information on masks and layout instructions

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